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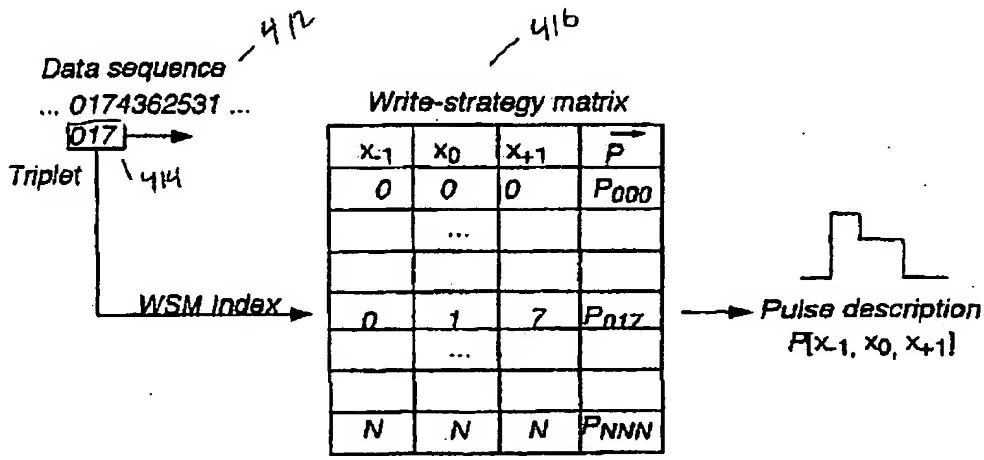

(57) Abstract: A system and method are disclosed for compensating during a data writing process for a transformation of input data by an optical disc data storage channel. A write strategy matrix (416) is derived that maps a plurality of input sequences (412) to a plurality of write strategy parameters. The input sequences (412) each include a plurality of input data elements. When an input sequence is received, the write strategy matrix (416) is used to determine a selected write strategy parameter that corresponds to the input sequence.

WO 01/57856 A1

WRITE COMPENSATION FOR A MULTI-LEVEL DATA STORAGE SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to co-pending U.S. Patent Application No. __________ (Attorney Docket No. CALMPO14) entitled "DC Control Of A Multilevel Signal" filed concurrently herewith, which is incorporated herein by reference for all purposes and U. S. Patent Application No. ____________(Attorney Docket No. CALMP013 entitled "Generating A Multilevel Calibration Sequence For Precompensation" filed concurrently herewith, which is incorporated herein by reference for all purposes.

FIELD OF THE INVENTION

The present invention relates generally to data storage. More specifically, a system and method for write compensation is disclosed.

BACKGROUND OF THE INVENTION

To maximize the storage capacity for a given volume of recording medium, it is desirable that a storage system have as high an information density as possible. As the information density increases, however, regions of data symbols increase their "interference" with both the recording and recovery of neighboring symbols. Without careful compensation for such interference, information may be distorted or lost. While it is possible to compensate for this inter-symbol-interference (ISI) after

readout, it is most desirable to compensate for ISI before recording to minimize noise enhancement resulting from data passing through the system.

DESCRIPTION OF LINEAR AND NONLINEAR ISI

Mathematically, ISI can be classified into two types: 1) linear ISI and 2) nonlinear ISI. Equation (1) formalizes this definition.

$$y(t) = h_0 + \sum_{n=1}^{\infty} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} h_n(\tau_1, \cdots, \tau_n) x(t-\tau_1) \cdots x(t-\tau_n) d\tau_1 \cdots d\tau_n \quad 1)$$

Here, the input time function x(t) is related to the output y(t) of a nonlinear system by a Volterra series with kernels h_n and additive zero-mean random noise $\eta(t)$. If the relationship between the input x(t) and output y(t) is linear, the first two terms containing h_0 and $h_1(\tau)$ are all that are necessary to completely describe the system. If the relationship between input and output includes nonlinear ISI, additional terms are necessary to describe the relationship.

Because of the increased computational complexity of processing or removing nonlinear distortions in a data storage system, it is desirable to make the system behave like a linear channel. In a linear channel, the relationship between the data input and the recovered signal can be completely described by a convolution of a linear filter with the input plus some additive random noise. From a coding and signal processing perspective, linearity is also desirable because historically there is a massive amount of theoretical work completed using linear channels. If a system can

be made to behave linearly, the techniques and knowledge resulting from this large body of work can then be applied.

In one embodiment of a multi-level (ML) optical data storage system, a long track is divided into a large number of small regular data cells. A laser is used to either write to or read from the individual cells. In such an optical storage system, a primary source of inter-symbol-interference (ISI) is the size of the reading and writing laser beam(s). As the data cells are packed together, the effects of neighboring symbols on both the formation and recovery of the data cells increases. During read-back, the reading laser beam illuminates a region of material that contains more than one data cell. As a result, the signal associated with the data cell of interest includes a linear convolution of signals from its neighbors.

During the writing process, effects such as thermal diffusion and the overlap from the tails of a Gaussian recording laser beam modify the state and response of neighboring cells. These effects produce nonlinear ISI. Diffraction effects (which are linear in amplitude, not intensity) also contribute to nonlinear ISI, as do non-ideal effects related to the read-back process such as nonlinearity of the photodiode and amplifiers. As a result of the above sources of ISI, the recovered data signal from a high-density recording and read-back system is corrupted by linear ISI, nonlinear ISI, and noise.

Variation in the recording process due to systematic variation of either the media response or the writing process also corrupts the recovered data signal. For example, variation of the size and shape of the reading beam during read-back may change the amount of inter-symbol-interference. Variation in the sensitivity of the

media during recording may change the size and shape of the recorded marks. Because these effects result in a systematic or deterministic source of error, the impact of many of these error sources could potentially be minimized through careful write compensation.

SHAPING THE CHANNEL

Figure 1A is a diagram illustrating Shannon's original abstraction of a general communication system. An information source 102 generates a signal x(t) which is transmitted by a transmitter 104 through the system or "channel" 106 to receiver 108 and a final destination 110. Along the path from the information source to the destination, the transmitted signal may be corrupted by both deterministic and random transformations. For example, a random noise source 112 is shown as an input to channel 106. It is the goal of the transmitter in a communication or storage system to compensate for the effects of such corruption. For example, a transmitter in a robust information system will add redundancy to combat the particular noise structure involved.

It would be useful if a way could be provided to write compensate for deterministic transformations that occur in the channel. Write compensation refers to compensation that occurs during the writing process. Read compensation refers to compensation that occurs during the reading process. Compensation in general may occur during the writing process and/or during the reading process.

If a particular reading system design can only recover data that has undergone a linear transformation, then any nonlinear transformation may be classified as noise. It would be desirable to remove as many deterministic sources of such "noise" as

possible using write compensation so that a reading system designed to compensate for linear transformations by the channel may be used effectively.

In general, both read and write compensation techniques are needed to maintain an acceptable signal to noise ratio (SNR) as information density increases on a storage medium. To the extent that write compensation can be used to cause the channel output to be linear or to conform to some desired target, the reading system may be simplified. Also, techniques are needed for compensating for transformations caused by various sources such as physical variations in a recording device or recording material response that occur as a result of manufacturing, wear, or environmental conditions.

SUMMARY OF THE INVENTION

Accordingly, compensation techniques are disclosed that allow the storage capacity for a given volume of recording medium to be increased without causing errors when data is read. In one embodiment, a method for shaping the input/output relationship for an optical data storage system such that the relationship is linear or other desired target is described. In one embodiment, a method for shaping the input/output relationship for an optical data storage system such that it maximizes the system signal-to-noise ratio is described. In one embodiment, a method for compensating for variations in a recording device or recording material response such as would occur in a typical manufacturing process or in a typical change of environmental operating condition is described.

It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, a device, a method, or a computer readable medium such as a computer readable storage medium or a computer network wherein program instructions are sent over optical or electronic communication links. Several inventive embodiments of the present invention are described below.

In one embodiment, a system and method are disclosed for compensating during a data writing process for a transformation of input data by an optical disc data storage channel. A write strategy matrix is derived that maps a plurality of input sequences to a plurality of write strategy parameters. The input sequences each include a plurality of input data elements. When an input sequence is received, the write strategy matrix is used to determine a selected write strategy parameter that corresponds to the input sequence.

In one embodiment, a system and method are disclosed for improving a write strategy matrix that maps a plurality of input sequences to a plurality of write strategy parameters. The input sequences each include a plurality of input data elements. A set of input sequences are written to an optical data storage channel using the write strategy matrix. The set of input sequences are transformed using a target channel model to obtain transformed data. Output data is recovered from the optical data storage channel. The recovered output data is compared to the transformed input data to determine a difference between the recovered output data and the transformed input data. The write strategy matrix is adjusted to decrease the difference between the recovered output data and the transformed input data.

In one embodiment, a system and method for deriving a write strategy matrix that maps a plurality of input sequences to a plurality of write strategy parameters is disclosed. The input sequences each include a plurality of input data elements. A first input sequence is written to an optical data storage channel. A first sequence of output data is recovered from the optical data storage channel. The first sequence of output data is used to map the plurality of data elements to a plurality of initial write strategy parameters. A second input sequence is written to the optical data storage channel using the initial write strategy parameters. The second input sequence includes a plurality of subsequences. A second sequence of output data is recovered from the optical data storage channel. The second sequence of output data is used to map the plurality of subsequences to the plurality of write strategy parameters.

In one embodiment, a system and method for deriving a write strategy matrix that maps a plurality of input sequences to a plurality of write strategy parameters is disclosed. The input sequences each include a plurality of input data elements. An input sequence is written to an optical data storage channel. The input sequence includes a plurality of subsequences. A sequence of output data is recovered from the optical data storage channel. The sequence of output data is used to map the plurality of subsequences to the plurality of write strategy parameters.

In one embodiment, a system and method of improving a write strategy matrix that maps a plurality of input sequences to a plurality of write strategy parameters is disclosed. The input sequences each include a plurality of input data elements. The set of input sequences is transformed using a target channel model to obtain a first set of transformed data. The set of input sequences is also transformed using a simulated

channel model to obtain a second set of transformed data. The first set of transformed data is compared to the second set of transformed data to determine a difference between the first set of transformed data to the second set of transformed data and the write strategy matrix is adjusted to decrease the difference between the first set of transformed data to the second set of transformed data.

In one embodiment, a system and method of improving a write strategy matrix that maps a plurality of input sequences to a plurality of write strategy parameters is disclosed. The input sequences each include a plurality of input data elements. A set of input sequences is written to an optical data storage channel using the write strategy matrix. The set of input sequences is transformed using a target channel model to obtain transformed data. The output data is recovered from the optical data storage channel. The recovered output data is compared to the transformed input data to determine a difference between the recovered output data and the transformed input data and the write strategy matrix is adjusted to decrease the difference between the recovered output data and the transformed input data.

These and other features and advantages of the present invention will be presented in more detail in the following detailed description and the accompanying figures which illustrate by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, wherein like reference numerals designate like structural elements, and in which:

Figure 1A is a diagram illustrating Shannon's original abstraction of a general communication system.

Figure 1B is a diagram illustrating a system with write compensation. A data generator 120 generates input data.

Figure 2 is a block diagram illustrating a write compensation system such as may be included in data compensator 122 of Figure 1.

Figure 3 is a diagram illustrating a more detailed breakdown data formatter 204 shown in Figure 2.

Figure 4A is a block diagram illustrating in further detail Writer 206 shown in Figure 2.

Figure 4B is a diagram illustrating how the write strategy matrix is used to look up successive write strategy parameters for a ML data sequence in one embodiment.

Figure 4C is a diagram illustrating a write strategy that uses a pulse having a variable power.

Figure 5 is a diagram illustrating in further detail reader 208 shown in Figure 2.

Figure 6A is a diagram illustrating in further detail write strategy calculator 214 shown in Figure 2.

Figure 6B is a graph illustrating an example of such a relationship and the typical nonlinear response of an optical media to a write strategy parameter.

Figure 6C is a graph illustrating an example of a sequential scan through pulse width and the resulting changes in reflectivity.

Figure 6D is a sample contour plot illustrating systematic signal error for a level 3 symbol as a function of its two nearest neighbors before and after precompensation.

Figure 7 illustrates an 8-level system where there is one narrow and one wide distribution.

Figures 8A and 8B illustrate the write compensation process used in one embodiment and described in detail above.

DETAILED DESCRIPTION

A detailed description of a preferred embodiment of the invention is provided below. While the invention is described in conjunction with that preferred embodiment, it should be understood that the invention is not limited to any one embodiment. On the contrary, the scope of the invention is limited only by the appended claims and the invention encompasses numerous alternatives, modifications and equivalents. For the purpose of example, numerous specific details are set forth in the following description in order to provide a thorough understanding of the present invention. The present invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the present invention is not unnecessarily obscured.

EXAMPLE MULTI-LEVEL OPTICAL DATA STORAGE SYSTEM

In one embodiment, this invention applies to the methods of writing marks on a phase change material as described in United States Patent Application No. 09/373,916, Attorney Docket No. CALMP007, filed August 12, 1999, entitled "High Density Data Write Strategy" which is herein incorporated by reference, hereinafter O'Neill et. al. As described therein, marks can be written in a manner such that their size can be less than the size of the focused spot of a writing laser. By forming marks smaller than the reading laser beam, the reflectivity of a region of material can be varied with great precision. The reflectivity of a region is controlled by varying the relative amount of material in crystalline and amorphous phases. The total amount of crystalline and amorphous material in a region is controlled by creating marks of various sizes or shapes. In turn, the mark size and shape is controlled by placing the leading and trailing edges of laser pulses such that the timing of a second laser pulse

further modifies the region of material irradiated by a first pulse. Additional modification of the mark size and shape results from controlling the time course of the laser power during the pulse.

When a reading laser is incident on a region of recorded material, the reflected light can be measured and the state of the region can be determined. The state of the region represents stored data. Multiple levels ($n \geq 2$) of reflectivity are possible. Different levels of reflectivity represent different data levels.

An ideal multi-level (ML) optical data storage system would read and recover a multi-level data pattern without any distortion or loss of data. In practice however, the data symbols are corrupted by deterministic and random processes during recording and read-back. Write compensation is used during the writing process to shape the relationship between the system input and output, thus controlling the deterministic or systematic sources of error.

Figure 1B is a diagram illustrating a system with write compensation. A data generator 120 generates input data. Data compensator 122 provides write compensation so that the input data to Data storage system 124 is transformed in a manner that compensates for the manner that Data storage system 124 transforms the data.

The Write compensation techniques described herein may be applied to any writing system that writes to any data channel, including data storage channels as well as data transmission channels. In general, a writing system that includes a laser will have various write strategy parameters. These write strategy parameter may include,

among other things, laser power and numerous parameters that control the shape and timing of laser pulses including pulse width, duty cycle, frequency and spacing of pulses, as well as various possible pulse shaping parameters. The input data controls the write strategy parameters, causing the input data to be written to the disc. Write compensation is implemented by altering the way that the input data is mapped to the write strategy parameters. In one embodiment, this is accomplished using a write strategy matrix (WSM).

In one embodiment that implements Write compensation for the writing system described in O'Neill et. al., input data is mapped to write strategy parameters that precisely control the time course of writing laser pulses. The write compensation process alters the mapping of the input data to the write strategy parameters in a manner that alters the precise time course of the writing laser power. More than one element of the input data sequence controls the writing laser power at any given time. In one embodiment, three input data elements: a previous, a current, and a subsequent input data element are used to determine a current set of write strategy parameters. In another embodiment, five input data elements are used to determine a current set of write strategy parameters. It is also possible to have different numbers of previous and subsequent input data elements or to have only a single input data element control the write strategy parameters.

WRITE COMPENSATION SYSTEM OVERVIEW

Figure 2 is a block diagram illustrating a write compensation system such as may be included in data compensator 122 of Figure 1. A test pattern that is created by a test data generator 202 is passed to a data formatter 204 where the data is organized

and various calibration and control patterns are added. The resulting formatted test pattern is separately passed through the physical channel (writer 206 and reader 208) and through a channel model 210.

The data sequence passed to the writer is converted to instructions that control the laser. This instruction set includes the specification of all relevant write strategy parameters for a given data sequence and is referred to as the write strategy-matrix. The recorded data is then read back by the reader, resulting in a recovered data pattern. The formatted test pattern that passes through the channel model results in a target data pattern. The write strategy-calculator (WSC) 214 compares the average recovered data pattern to the target data pattern and calculates an update to the write instruction set contained in the write strategy matrix. Thus, the write strategy calculator changes the write strategy matrix and thereby changes how the input data sequence is mapped to the relevant write strategy parameters.

To measure the result of the update to the write strategy matrix, the test pattern is written and read again and the above procedure is repeated. If the mean-squared-difference between the target and recovered data pattern is less than a maximum threshold error value, the procedure terminates successfully. If the difference remains above the maximum threshold error value, the procedure iterates until the error converges to a value less than the maximum threshold error value.

In one embodiment, the channel model is not fixed during the iterations. In this embodiment, a best linear fit to the data is computed as the channel model and input to the write strategy calculator. In another embodiment, the channel model is

fixed to a particular target. In another embodiment, the signal dynamic range is optimized as part of the write strategy iteration process.

TEST PATTERN GENERATOR AND FORMATTER

Various control sequences may be added to the test pattern of interest to aid in the recovery of data. The most significant of these types of control sequences include synchronization marks, timing and alignment sequences, and automatic-gain-control (AGC) sequences such as are described in United States Patent Application No. 09/253,808, Attorney Docket No. CALMP009, filed February 18, 1999, entitled "Architecture For Reading A Multi-Level Signal From An Optical Disc" which is herein incorporated by reference. Figure 3 is a diagram illustrating a more detailed breakdown data formatter 204 shown in Figure 2. A data generator 302 outputs data to a sync mark insertion block 304. The output of sync mark insertion block 304 is input to a timing sequence insertion block 306. The output of timing sequence insertion block 306 is input to a AGC sequence insertion block 308.

In one embodiment, two types of test patterns are used in the write compensation process. Type I patterns are used in determining the level placements and initializing the write strategy matrix and type II patterns are used in the write strategy matrix update process.

The process of initializing the write strategy matrix is important for proper functioning of the write compensation procedure. The initialization procedure begins with a measurement of the relationship between the write strategy parameters and the resulting reflectivity of the data mark. Based on the output detected when the type-I pattern is written to the disc, the write strategy calculator (WSC) chooses write

strategy parameters that span about 10% less than the full range of the media response. This choice maximizes the recovered signal strength. Figure 6B is a graph illustrating an example of such a relationship and the typical nonlinear response of an optical media to a write strategy parameter. Points A and D label the minimum and maximum reflectivity of the media achieved by the write strategy. Points B and C mark the useable dynamic range for the initial write strategy matrix values (typically 10% less than the saturated response). The variance of all parts of this curve are also measured and used to optimally place the levels with the techniques described below.

The purpose of the type-I pattern is to sample reflectivity values resulting from a particular choice of write strategy parameters. The resulting data is then used by the write strategy calculator to initialize the write strategy matrix. An example of a type-I pattern for the write strategies outlined in United States Patent Application No. 09/373,916, Attorney Docket No. CALMP007, filed August 12, 1999, entitled "High Density Data Write Strategy" which is herein incorporated by reference, hereinafter O'Neill et. al. is given below. In the example given, the laser power associated with each pulse is fixed and the pulse width is chosen as the write strategy parameter that is varied by the input data to control the reflectivity of a mark.

It should be noted that in this example, a single write strategy parameter is varied to modulate the output. In other embodiments, a combination of write strategy parameters are used. The combination of write strategy parameters may be specified by the write strategy matrix or, alternatively a single index may be determined by the write strategy matrix that maps to a plurality of write strategy parameters.

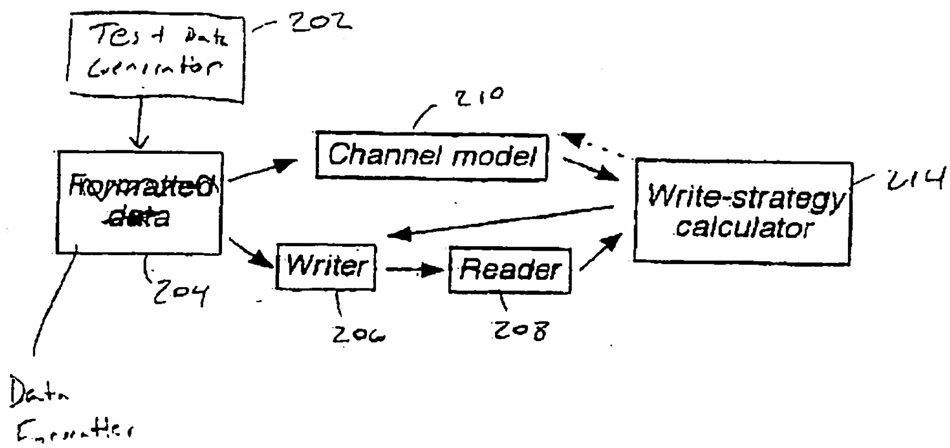

FIG. 2. Write compensation system

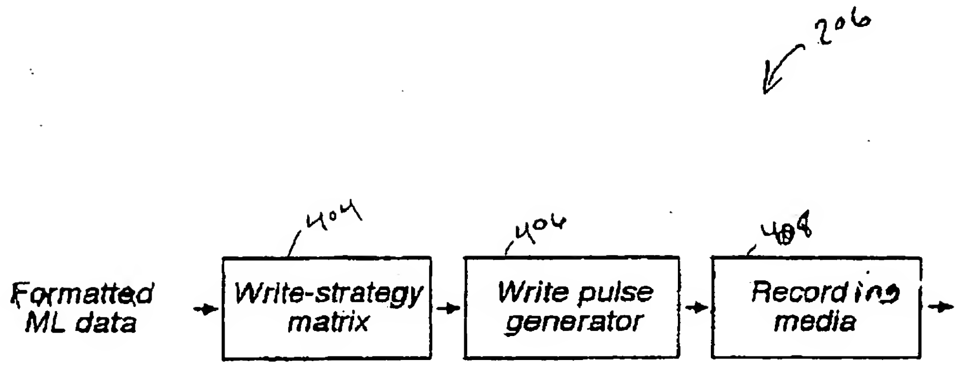

FIG. 4A. Data writer

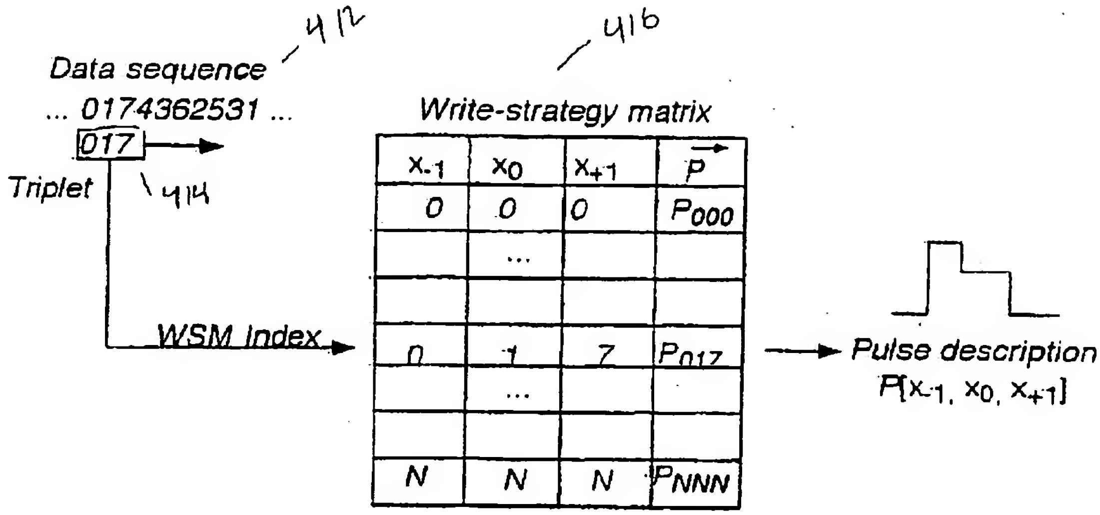
412
416
Data sequence
... 0174362531 ...
017
Triplet
414
Write-strategy matrix
x-1
x0
x+1
P
0
0
0
P000
...
WSM Index
0
1
7
P017
...
N
N
N
PNNN
Pulse description
P[x-1, x0, x+1]

Figure 4B

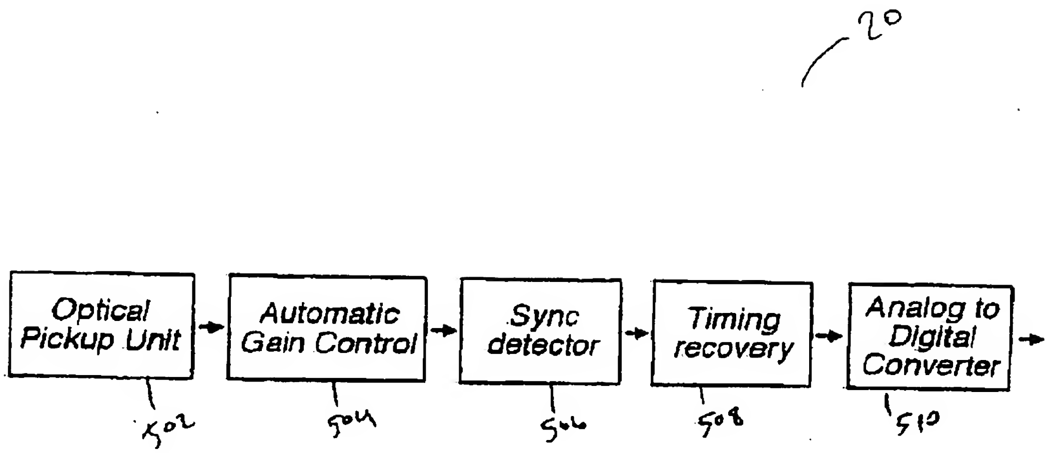
20
Optical Pickup Unit
Automatic Gain Control
Sync detector
Timing recovery
Analog to Digital Converter
502
504
506
508
510

Figure 5